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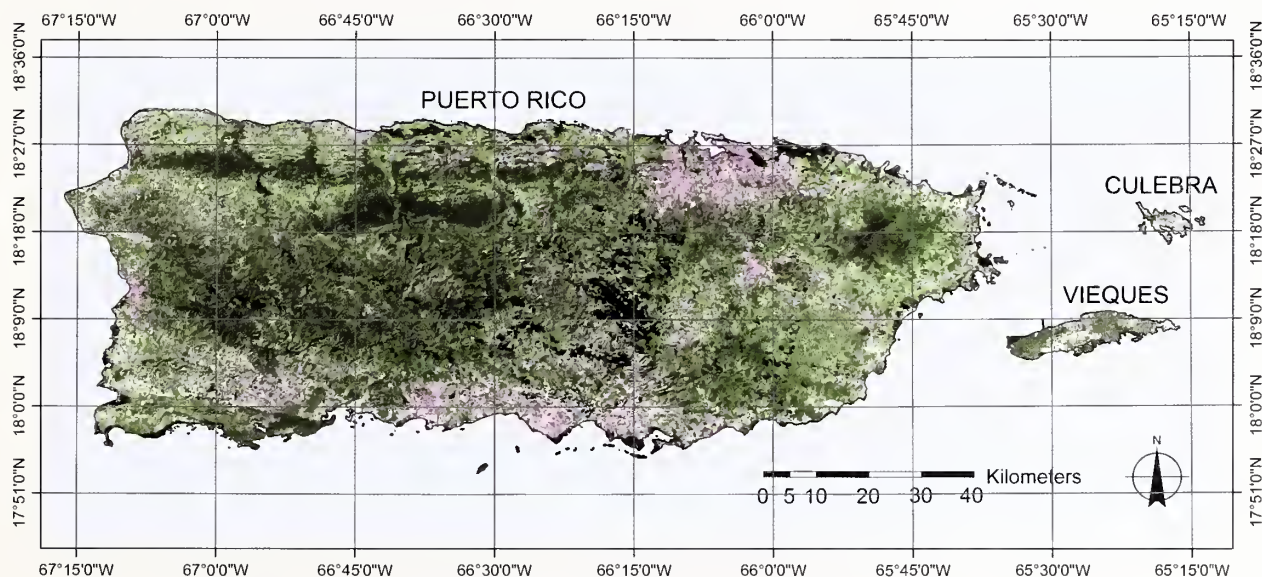
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Creating Cloud-Free Landsat ETM+ Data Sets in Tropical Landscapes: Cloud and Cloud-Shadow Removal

Sebastián Martinuzzi, William A. Gould, and Olga M. Ramos González



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Abstract

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Clouds and cloud shadows are common features of visible and infrared remotely-sensed images collected from many parts of the world, particularly in humid and tropical regions. We have developed a simple and semiautomated method to mask clouds and shadows in Landsat ETM+ imagery, and have developed a recent cloud-free composite of multitemporal images for Puerto Rico and its adjacent islands that can be used for a variety of landscape analyses. Our assumption is that if clouds and shadows can be identified in a reference image, they can be replaced with data from other dates. We created cloud masks by using Landsat ETM+ band 1 (blue) and thermal band 6.1. Additionally, Landsat ETM+ band 4 (near infrared) and parameters of sun angle, topography, and cloud-shadow projection were used for directing and masking shadows. This methodology was applied to a set of 18 images from 1999 to 2003 to develop an island-wide image that is 96.5 percent cloud free. We considered the seasonality of the imagery when selecting reference images and building the mosaic in order to minimize variation in reflectance related to dry or wet season canopy characteristics. We developed a higher resolution data set by merging the 15-m resolution panchromatic band with the 30-m resolution Landsat ETM+ data. The methodology developed is simple and straightforward to use wherever obtaining cloud-free image data sets is desirable and can be integrated into other efforts that demand an accurate method for the identification of clouds and shadows.

Keywords: Remote sensing, clouds, shadows, mask, Landsat ETM+, Puerto Rico.

Introduction

Clouds are common features of visible and infrared remotely-sensed images collected from many tropical, humid, mountainous, and coastal regions of the world. Puerto Rico is a mountainous tropical island with pressing needs for readily applicable methods to develop Landsat ETM+ cloud-free scenes for analyses of current land cover and land-cover change. Landsat data has been used in Puerto Rico for high temporal resolution analyses of land-cover change related to urban expansion and regeneration of forests over abandoned agricultural land (Grau et al. 2003; Helmer 2004; Helmer and Ruefenacht 2005; Lopez et al. 2001; Thomlinson et al. 1996; Ramos-Gonzalez 2001), estimation of forested area, identification of forests types (Helmer et al. 2002), and current land-cover classification, a key component for mapping habitats and biodiversity as part of the Puerto Rico Gap Analysis Program (Gould 2005). Cloud-free data acquisition for a single date is difficult or impossible for the entire island, particularly for higher elevations where a high percentage of the protected forest resources are located. In the past, the continued presence of clouds in imagery has reduced the amount of island-wide data available, and as a result has restricted analyses to those years for which low cloud cover images exist (1985, 1991, and 1992). Cloud-free image data sets are useful both for the creation of composites and for comparison of temporal variation in spectral signals. In the creation of composite imagery, data can be radiometrically corrected, mosaicked, and analyzed as a single image for classification of general land cover types, or scenes can be classified individually and mosaicked postclassification.

The Puerto Rican landscape represents a challenge for clouds and shadow identification in Landsat ETM+ images owing to the complexity and heterogeneity of land cover (including different forest types and a variety of high-reflectance surfaces such as urban, barren, quarries, rocks, salt mining, sand, pastures and agricultural lands), and topography. In the visible and near-infrared spectral regions of Landsat ETM+ images, clouds are generally characterized by reflectance higher than the underlying (land or ocean) surface. However, under certain surface conditions, such as urban/built-up areas (as for ice and snow in temperate and cold regions), the reflectance difference between cloud and underlying surface can be insufficiently low or even reversed (Li et al. 1999, Schröder et al. 2002). Optical remote sensing images also have the problem of cloud shadows. The spectral irradiance reaching the ground in cloud-shadow areas is both reduced in intensity and changed in its spectral properties (Choi and Milton 1999), similar to that of topographic shadows. The presence of two additional thermal bands in Landsat imagery

(bands 6.1 and 6.2) allows for the analysis of the surface in terms of ground or canopy surface temperatures (Melesse and Jordan 2002). In these bands, clouds, tree foliage, and damp ground appear in dark tones (cooler), whereas grassland and other low-lying vegetation, dry ground, concrete, and asphalt appear in brighter tones (warmer) (Jensen 2000).

The development of cloud-free composites involves both the identification of cloud features as well as distinguishing cloud shadows from topographic shadows. Various techniques have been developed to minimize the effect of clouds and cloud-shadows (Ackerman et al. 1998, Choi and Milton 1999, Helmer and Ruefenacht 2005, Li et al. 1999, Liew et al. 1998, Milton and Choi 1999, Schröder et al. 2002, Song and Civco 2002). We used optical and thermal spectral characteristics as well as geographic position to identify cloud and cloud shadows. Analysis of spectral reflectance in different bands is essential to identifying features in the images. Song and Civco (2002) used the brightness value in Landsat TM bands 1 (blue) and 4 (near infrared) to detect clouds and shadows in Madagascar. We added thermal information from Landsat ETM band 6.1 to spectrally separate clouds from similarly responding features, such as urban/built-up lands. Although cloud shadows and topographic shadows are not spectrally distinguishable in optical images, they can be identified by geographic position. The direction of the shadow occurrence relative to the cloud is the same for the entire scene as it depends on the sun illumination angle, a constant for any given scene. The location, form, and dimensions of any cloud shadow depend on the cloud shape and elevation, topography, and the sun illumination angle.

The development of masks for identifying clouds and cloud shadows is our solution to develop a final cloud- and shadow-free Landsat ETM+ composite image. Our principle is to identify clouds and shadows in a reference image and replace them with cloud- and shadow-free parts from other dates. Masks facilitate operations such as subtraction and replacement of specific areas, as well as buffering, intersection, and union.

We have developed simple semiautomated procedures to generate cloud and shadow masks in tropical regions for use in the creation of cloud-free composite Landsat ETM+ imagery, by using multiple recent images acquired at different times over the same region. Our goals in developing these methods were to make use of spectral and geographic information to facilitate the identification of cloud cover, separate cloud and topographic shadows, and minimize the needed masked areas.

In addition to the masking method, we have incorporated additional processes for the creation of the final imagery data set. We sought to minimize differences in reflectance owing to atmospheric conditions by correcting for Rayleigh scatter and differences in seasonality of vegetation by using, whenever possible, imagery acquired during the same season. Aside from Rayleigh scatter correction, we have not incorporated any methods to normalize systematic scene-to-scene radiometric variation such as dark object subtraction (Chavez 1996). This would be advisable when classifying a composite image but unnecessary when classifying individual scenes before mosaicking. We also improved our ability to separate subpixel features (for urban or mangrove areas) by enhancing the spatial resolution incorporating the higher (15-m) resolution of the panchromatic band into the multispectral images. We have developed a useful image data set for the islands of Puerto Rico, Vieques, Culebra, and additional small islands within the Puerto Rican Archipelago. The methods to develop this data set will work equally well throughout the Caribbean basin and similar regions, and with Landsat ETM+ imagery acquired over a range of dates.

Data and Methods

Four Landsat ETM+ path-rows (4-47, 4-48, 5-47, and 5-48) are necessary to cover Puerto Rico and its adjacent islands of Vieques and Culebra. Our data set is composed of 18 images acquired between September 1999 and February 2003. During 2002, no images were incorporated owing to persistent dense cloud cover. The complete process leading to the resulting cloud- and cloud-shadow-free composite image can be accomplished in four major steps outlined in our methods, and subsequently applied to our 18 images. These include atmospheric correction, cloud and cloud-shadow masking, resampling and addition of the panchromatic band, and image selection and composition.

Atmospheric Correction

Atmospheric correction is necessary to put multitemporal data on the same radiometric scale, in order to create an image data set with compatible scenes that is useful for classification and monitoring terrestrial surfaces over time (Song et al. 2001). We used a model developed by the Institute for Astronomy and Space Physics IAFE-CONITET to convert radiance to reflectance corrected by Rayleigh scatter (Paolini et al. 2004). The input parameters required for running the model are included in the image header and include gain, bias, sun elevation angle, solar azimuth angle, and date. The model is described by the following formula:

$$\text{Surface reflectance} = \delta \times (L_{\text{c}} - L_{\text{Rayleigh}}) \times r^2 / E_0 (\cos/\delta) ,$$

Where

L_{c} = at satellite radiance = $\text{gain}_{\text{c}} \times \text{DN} \times \text{bias}_{\text{c}}$,

L_{Rayleigh} = radiance owing to Rayleigh scatter,

E_0 = extraterrestrial irradiance,

r = Earth-Sun distance, and

δ = Sun elevation angle.

Each scene was processed using this formula before proceeding with the cloud and shadow masking.

Cloud and Cloud-Shadow Masking

This involves two main procedures: (1) identifying clouds and developing a mask by using Landsat ETM+ brightness values (DN) in optical band 1 (blue) and in thermal band 6.1 and (2) developing a final cloud and cloud-shadow mask by using the cloud mask, the brightness values of shadowed areas in band 4 (near infrared), and the geometric relationship between shadow position and the clouds (i.e., parameters of cloud projection) (fig. 1).

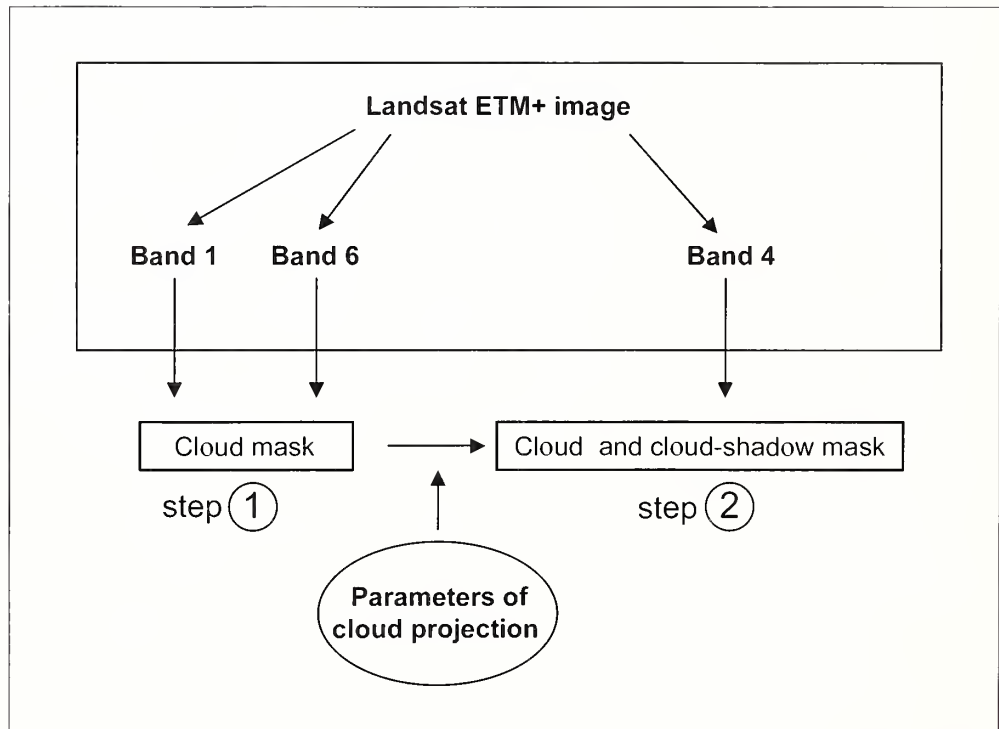


Figure 1—Steps for masking clouds and cloud shadows. In step 1, the range of reflectance values for clouds are determined by visually inspecting the range of cloud types and digital numbers (DNs) in band 1 (blue) and in thermal band 6.1, and then selecting DN's in this range. In step 2, band 4 (near infrared), the geometric relationships of shadows to clouds, and the clouds mask, were used in the identification of cloud shadows.

Cloud Masking

The spatial resolution of the thermal band 6.1 was resampled from 60- to 30-m pixels, and subsequently bands 1 and 6 were analyzed by using the following procedures:

- Brightness values for clouds were identified by visual analysis. For band 1, DN values between 120 and 255 include clouds as well as urban, barren, quarries, rocks, and sand. For band 6, DN values of 102 to 128 include both clouds and densely forested areas.
- A mask was created for band 1 and for band 6 by using the previous values. A three-pixel buffer was added to incorporate mixed pixels from cloud borders that could not be incorporated by brightness value analysis.
- The intersection of both masks results in a final clouds mask, which was also buffered by three pixels (fig. 2).

Cloud-Shadow Masking and Obtaining the Final Cloud and Cloud-Shadow Mask

The first step in the creation of a cloud-shadow mask was to estimate the potential shadowed areas in the reference image by projecting the cloud mask on the land, and considering the effects of Sun illumination angle, topography, and cloud elevation (fig. 3). For this, an identifiable feature or point observable in both a cloud and its shadow was located in the image, ideally over low-elevation landscapes where clouds are at the greatest height above land (assuming a relatively constant elevation of clouds affecting the image). The difference in X and Y coordinates for these points is an estimation of the horizontal “shift” between cloud and shadow positions. A mask of potential cloud-shadow areas was created by displacement of the cloud mask based on the horizontal shift. To account for possible variations in the shadowed areas related to variation in cloud elevation and topography, a 10-pixel buffer was added. The resulting mask includes and overestimates all the areas with potential cloud shadows. Within these areas, the brightness values in band 4 were used to differentiate cloud-shadow areas from nonshadowed areas (fig. 2). In our imagery, the DN range 17 to 66 includes cloud shadows, but also some topographic shadows, certain urban areas, and land-water transition zones that are within potential cloud-shadow areas. Finally, cloud-shadow areas were added to the cloud mask to obtain a final cloud and cloud-shadow mask.

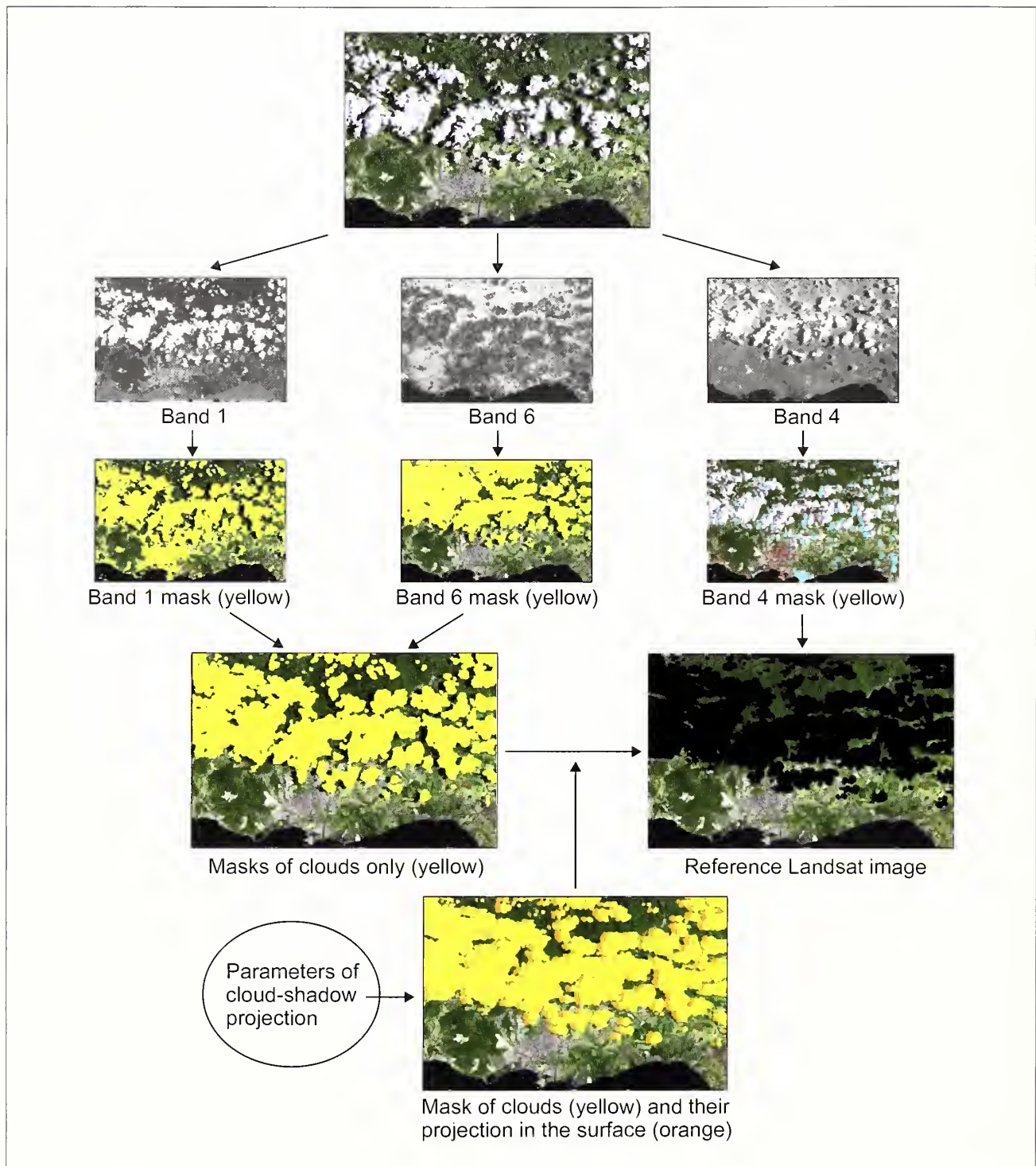


Figure 2—Flow chart illustrating cloud and cloud-shadow masking steps in an area of heterogeneous land cover and high cloud cover. A Landsat ETM+ subset image of the town of Ponce in southern Puerto Rico includes urban areas, cultivated land, pastures, quarries, barren areas, beaches, rivers, clouds, and shadows. The image is shown in band combination R (7) G (5) B (3). Three masks were developed from bands 1, 6, and 4, respectively. Band 1 mask (in yellow) includes clouds and some urban, barren, quarries, rocks, and sand. Band 6 mask (in yellow) includes clouds and some densely forested areas. Band 4 mask (in blue) includes cloud shadows, topographic shadows, certain urban areas, and land-water transition zones. Band 1 and band 6 masks are intersected for a mask of clouds only (yellow). This is joined with a cloud-shadow mask to develop the cloud-free reference image.

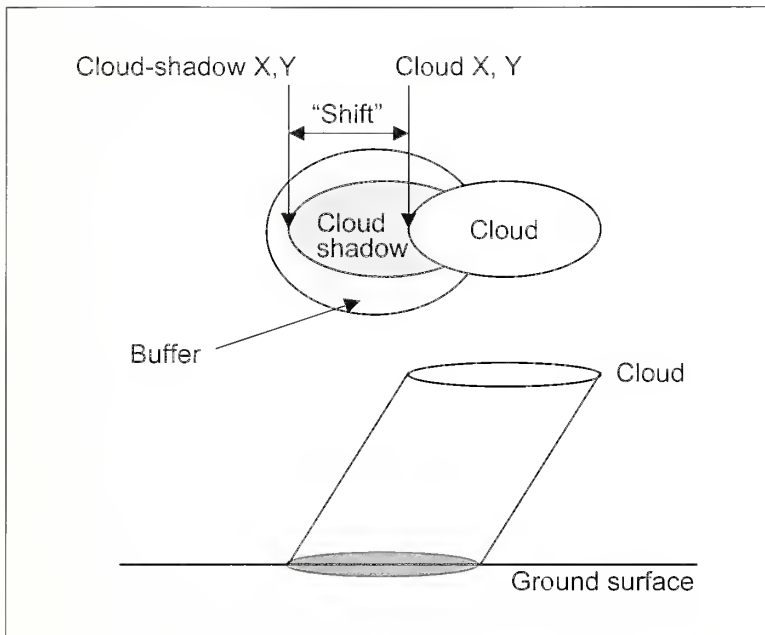


Figure 3—Representation of the geometric shift of cloud shadow plus buffer mask along X and Y axes that is determined by cloud elevation and Sun angle.

Resolution Enhancement and Image Composition

One of our immediate uses of this composite image data set is to study land use and urban developments. Because much of the spatial variability in developed and undeveloped surfaces is related to roads and buildings that are subpixel features at 30-m resolution, we enhanced the spatial resolution of the images by merging the visible and IR bands (30- by 30-m pixel) with the panchromatic band (15- by 15-m pixel) in all of our scenes by using Principal Component Analysis and Cubic Convolution Resampling in ERDAS Imagine 8.7. For the image composition the most cloud-free scene from each path/row was selected as the reference image, i.e., the top scene for each path/row in the mosaic. Cloud and cloud-shadow areas in reference images were replaced with data from other dates.

Results

Our set of images ranged from 16.35 to 74.64 percent cloud and cloud-shadow coverage and contained acquisition dates in both the wet and dry seasons in Puerto Rico (table 1). Over half of the scenes had greater than 50 percent cloud cover. Two scenes were from 1999, eight from 2000, seven from 2001, none from 2002, and one from 2003. We qualitatively ranked the images into dry or wet season assisted by monthly rainfall data from different locations in the island, and visual analysis of the images. Seven scenes were from the dry season, nine from the wet season,

Table 1—Landsat ETM+ imagery data set description, including reference image number, path, row, region covered, acquisition date, season, and percentage of cloud cover

Reference image	Path	Row	Region	Acquisition date	Season (wet or dry)	Cloud cover
						<i>Percent</i>
1	5	47	NW and Center PR	January 22, 2003	d	27.66
2	5	47	NW and Center PR	September 10, 2000	w	55.80
3	5	47	NW and Center PR	July 27, 2001	w	47.01
4	5	47	NW and Center PR	March 5, 2001	d	53.62
5	5	48	Southwest PR	September 10, 2000	w	52.86
6	5	48	Southwest PR	July 11, 2001	d	39.84
7	5	48	Southwest PR	November 13, 2000	w	16.35
8	4	47	Northeast PR	May 14, 2000	d-w	40.81
9	4	47	Northeast PR	September 17, 1999	w	62.74
10	4	47	Northeast PR	January 25, 2001	w	62.08
11	4	47	Northeast PR	February 26, 2001	d-w	58.43
12	4	47	Northeast PR	March 27, 2000	d	34.65
13	4	47	Northeast PR	August 2, 2000	d	69.00
14	4	47	Northeast PR	January 9, 2001	w	52.24
15	4	48	Southeast PR	September 17, 1999	w	64.40
16	4	48	Southeast PR	August 18, 2000	d	46.76
17	4	48	Southeast PR	January 25, 2001	w	74.64
18	4	48	Southeast PR	March 27, 2000	d	27.39
Final composite						3.50

and two were transitional. The significance of identifying seasonality in the scenes is to maintain, when possible, phenological homogeneity between images composing the mosaic.

For the mosaic, one image from each path/row was selected as the reference image, i.e., the top scene for each path row in the mosaic. To determine which scene would be our reference, we chose scenes low in cloud cover and from the dry season. The primary reference image was path/row 5-47 from January 2003 that covered the north, east, and center of the island and had low cloud cover (27.66 percent). In addition, we used a Landsat 5 image from 1985, the only completely cloud-free image for eastern Puerto Rico at the time, to replace 5600 ha (0.65 percent of the island) of medium- and high-elevation forested areas located within the Caribbean National Forest that had persistent cloud cover in all the recent images. We produced a 15-m Landsat ETM+ composite image data set that is 96.5 percent cloud and cloud-shadow free. The final mosaic (fig. 4) is displayed by using the band combination R (7), G (5), B (3). Forested vegetation shows up as dark green, grassland and agricultural areas as pale green, urban and, dry agricultural areas as violet. Remaining cloud-covered areas (3.5 percent) are in black and will be replaced as cloud-free imagery becomes available.

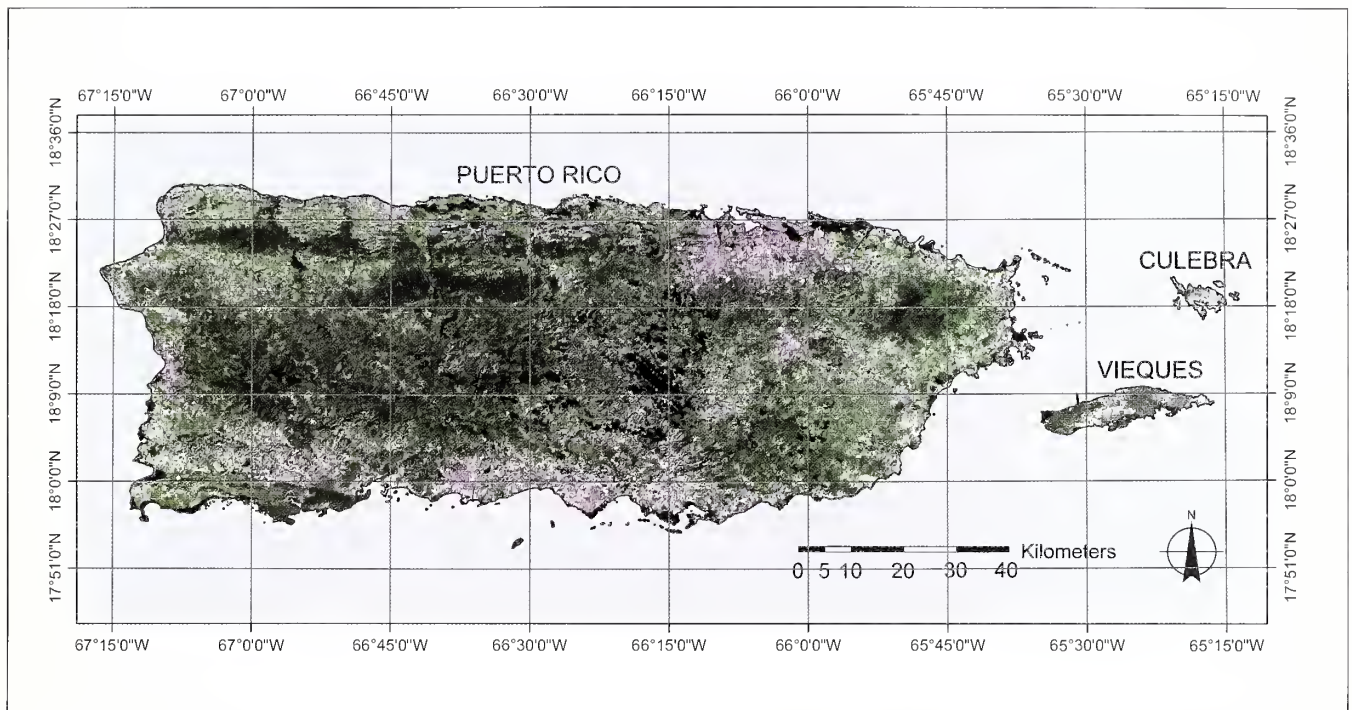


Figure 4—Composite Landsat ETM+ image for Puerto Rico, Vieques, and Culebra, developed from a set of 18 images acquired between 1999 and 2003.

Discussion

Remote-sensing tools and applications have become deeply integrated in a wide range of theoretical and applied ecological modeling. New problems and questions, new remote-sensing technologies, better computing facilities, and more sophisticated analyses are continually being developed. Advancements in optical remote sensing are particularly useful for characterizing landscapes in fast-changing environments where scientific expertise must keep pace with development and the needs of society. The ability to contribute to these advancements and use them for research and management issues depends on the ability to acquire and build data sets with complete historical and current coverage. It will always be difficult to obtain cloud-free data in cloud-prone environments, but applying simple methods of cloud and cloud-shadow detection, atmospheric correction, and image mosaicking can be beneficial in developing useful remote-sensing data sets.

The major benefit of this methodology is its simplicity and straightforward approach, allowing cloud-free-image analyses by using the most comprehensive image data set for the study area and objectives. The distinctive point of our study is that we semiautomatically derive cloud and cloud-shadow masks from simple parameters. There are a number of instances in which this methodology can prove useful:

- Our method for developing a cloud and cloud-shadow mask is useful for preparing the imagery for pixel-replacement procedures. Innovative strategies for the development of cloud-free imagery use regression trees to predict values underneath clouds and cloud shadows in reference scenes based scenes from other dates (Helmer and Ruefenacht 2005). The input images need to have clouds and cloud shadows already masked, which is originally solved by a combination of unsupervised classification and manual editing.
- Our method increases the functionality of Landsat TM and ETM+ data that have been acquired since 1982, and had been underutilized because of the presence of clouds, and adds to the set of images suitable for conducting modeling and land-cover change studies.
- The method highlights the importance of the thermal band in the Landsat TM and ETM+ sensors for the creation of cloud- and shadow-free images in tropical and other landscapes.
- The method can be incorporated into the research effort of the U.S. Geological Survey (USGS) Landsat 7 Project at the USGS EROS Data Center to increase the utility of the Landsat 7 ETM+ data for images acquired in tropical regions.

The limitations of our methodology include, for the creation of the masks, the inability to discriminate between cloud shadow and topographic shadow within areas of potential shadow occurrence, and in the mosaicking process, issues common to any multiscene or multirate composite, i.e., atmospheric differences and temporal changes related to seasonality of vegetation or land use. We found that the atmospheric correction for Rayleigh scatter eliminated some of the variability between scenes related to atmospheric conditions. The best-case scenario is to identify and minimize likely temporal changes, or develop models to estimate expected spectral responses related to seasonality. In a region like Puerto Rico, with areas of the island having strong vegetation responses to dry and wet seasons, the best-case scenario would be to develop image composites for both the dry and wet seasons.

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English Equivalents

When you know:	Multiply by:	To get:
Meters (m)	3.28	Feet
Hectares (ha)	2.47	Acres

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